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The mechanism of bubble detachment from a wall at zero and negative gravity

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An experiment has been carried out in which air bubbles were caused to grow isothermally at a vertical wall between two closely spaced horizontal plates. The experiment gives an approximate representation in two dimensions for the growth of a vapour bubble at a wall under some conditions of subcooled boiling in zero gravity. Although the effect of gravity was virtually eliminated in the experiment, it was found that a bubble could still detach itself from the wall, apparently owing to the effects of surface tension and inertia.

Also, bubbles were seen to detach from a wall despite the presence of a slight gravity force directed to oppose such detachment.

1. Introduction

It is generally accepted that the high heat-transfer rates from a heated solid wall to a boiling liquid can be attributed to the growth and departure of vapour bubbles. Many theories and correlations for the heat transfer depend on departure parameters such as the frequency of departure of bubbles and their size at departure. Thus to understand nucleate boiling and the associated high heat fluxes, a good grasp of the factors influencing bubble departure is of primary importance.

The forces acting to separate a bubble from a heated wall, which in effect bring cooler liquid into contact with the wall, have been widely studied by many investigators (Saini, Gupta & Lal 1975; Akiyama 1970; Howell & Siegel 1967; Han & Griffith 1965; and others), but the mechanism of detachment and the balance of the forces involved are still not fully understood.

Forces due to gravity, viscosity, liquid inertia and surface tension are all known to act on the bubble throughout its growth and departure. The influence of each of these forces changes continuously and in such a complex manner that the problem is difficult to analyse. However, by removing one of them, that due to gravity in this experiment, the problem can be simplified and the role of the remaining forces can be clarified.

The purpose of this paper is to draw attention to a mechanism of bubble detachment observed in an experiment where the effect of gravity has been eliminated. Air bubbles were blown in water against a vertical wall enclosed between two closely spaced horizontal Perspex plates. The movement of the liquid around the flattened bubble was thus restricted to a plane in which the component of gravity was zero. The apparatus and the experimental procedure are described in detail in the next section.

It has been found that under certain circumstances the bubble detaches completely from the wall and comes to rest some distance away. The detachment is attributed to the gas–liquid surface tension and to the inertia of the liquid. For a particular liquid the distance from the wall at which the bubble comes to rest has been found to depend upon both the volume growth rate and the final volume of the bubble.

From tests with slightly inclined plates it has been found that bubbles can also detach in the presence of slight gravity forces directed to oppose such detachment.

The experimental results support Madhaven & Mesler (1970), who argue that "on a non-growing bubble the gas–liquid surface tension force can be a dominant factor causing bubble detachment". On the other hand, the mechanism described here differs from some other mechanisms suggested. Isshiki & Tamaki (1963) considered the mechanism responsible for the ejection of a bubble to be the liquid inertia generated by the rapid initial growth. Kotake (1966, 1969) supported the same theory of an inertia force. Keshock & Siegel (1964) and later Rehm (1965) regarded the buoyancy force as the sole motive force for detachment.

2. Apparatus

The main part of the system used is shown in figure 1. A bubble can be formed between the two parallel Perspex plates (*b*) by injecting air through a 1 mm diameter hole (*m*) drilled in the lower plate. The bubble grows against the vertical face of a brass plate separating the two Perspex plates. This face acts to distort the growing bubble and is analogous to the heated wall in boiling.

The air is supplied to the bubble via a specially designed valve. The body of the valve (*j*) is a stainless-steel block with a flat upper face fixed against the lower Perspex plate. Two brass pistons slide freely along a bore machined in the block and are connected by means of a theaded rod (*e*) so that the gap between them can be adjusted. Initially, piston (*d*) (figure 1) is positioned between the hole (*m*) and the supply of compressed air (*l*). Compressed air from another supply (*k*) drives the pistons until piston (*c*) takes the position originally occupied by piston (*d*). Air flows into the gap between the two plates for a period starting when the trailing edge of piston (*d*) uncovers the hole (*m*) and ending when the leading edge of piston (*c*) covers it again.

The duration of the air injection can be controlled by adjusting the gap between the two pistons or by regulating the pressure of the air driving the pistons. The growth rate of the bubble can be controlled by regulating the pres sure of the air injected. With this arrangement air bubbles of different sizes and growth rates can be produced.

Prior to each experiment, the plates and the valve were thoroughly cleaned with acetone. Double-distilled water was used and the air from the two air supply bottles was carefully filtered to avoid contamination of the water.

A high-speed 16 mm STALEX WS 1-C camera was used to record the

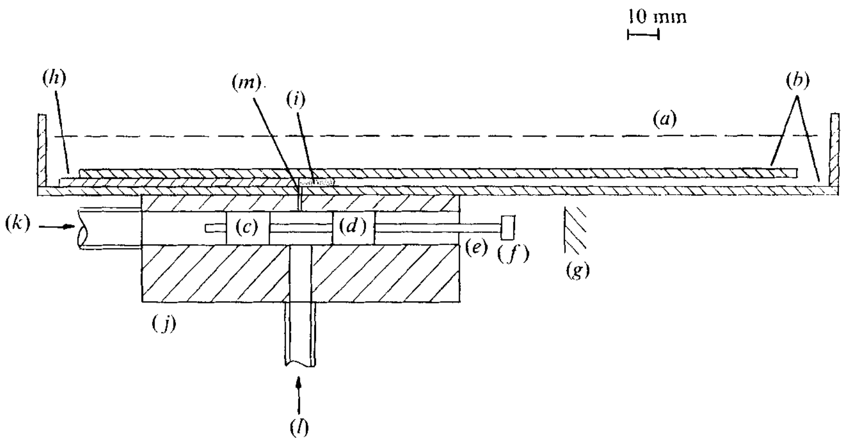

FIGURE 1. Apparatus for studying two-dimensional bubbles. (*a*) Water level. (*b*) Closely spaced plates. (*c*) Brass piston. (*d*) Brass piston. (*e*) Threaded rod connecting pistons. (*f*) Rubber pad. (*g*) Crash barrier. (*h*) Brass plate. (*i*) Air bubble. (*j*) Stainless-steel block. (*k*) Supply of pressurized air to drive the pistons. (*l*) Supply of pressurized air to the bubble. (*m*) 1 mm diameter hole through which the air is supplied to the bubble.

behaviour of the bubbles. In cases where only the final position of the bubble was important, a 35 mm still camera was used. To get a sharp and clear interface on the photographs, the lower Perspex plate and the brass plate were sprayed white. Only a small square where the bubbles grew was painted black. The system was illuminated from above and light from the white surroundings was reflected at the bubble interface, which contrasted against the black background (figures 2, 3 and 5, plates 1 and 2). On the photographs shown, the transverse line on which the bubble grows represents the wall, but the other boundaries of the black zone are not walls.

In the course of the experiments, different gaps between the two plates were tried. By increasing the distance between the two plates their shearing effect was minimized. On the other hand, the gap had to be kept sufficiently 'small' so that the flow between the plates was very nearly two-dimensional.

For a gap of 0·4 mm, the resistance of the plates was high enough to prevent bubble departure in all cases. For a gap of about 6·35 mm the bubbles were in contact with the top plate over a significantly larger area than with the lower one. For runs with gaps of 3·17 and 1·59 mm and with similar bubble sizes and growth rates, the bubble was removed to nearly the same distance away from the wall for as long as the bubble diameter was greater than about 5 mm (Malcotsis 1975). The plate shearing effect appeared to be nearly the same in both cases, and all further observations were made with a gap of 3·17 mm.

Using that gap and observing bubbles from the side, using the high-speed camera, it appeared that for the range of growth rates concerned the air–liquid interface was symmetrical during the growth and the bubble reached practically to the upper and lower plates, apart from a thin residual layer left between the bubble and each of the plates.

3. Results

3.1. *The mechanism of departure*

For zero-gravity conditions, the detachment mechanism is illustrated in figure 2 (plate 1). Air is injected for nearly 12 ms and throughout the growth the bubble remains nearly semicircular in plan apart from a thin layer (microlayer) arising from viscous effects near the wall.

When the air supply stops, the bubble starts rounding off owing to the surface-tension stresses. During the rounding-off process the liquid attains some momentum, which makes the interface overshoot the circular equilibrium shape (a more complex variant of the classical oscillation of a bubble). Now the existence of the solid wall causes asymmetry and examination of figure 2, 300–408 ms, shows that the surface curvature of the bubble increases continuously towards the wall. Thus, assuming constant gas pressure, there is a pressure gradient driving liquid towards the base of the bubble with the effect of removing it from the wall.

3.2. *The effect of bubble size on departure*

Figure 3 (plate 1) illustrates the behaviour of a larger bubble. The pressure of the air injected into the bubble is the same as for figure 2, but the air injection time is longer.

Once again, when the air injection stops the bubble is almost semicircular in plan. However, the surface-tension stresses are smaller and the rounding-off process is much slower. As a result, the momentum given to the liquid is not sufficient for the interface to overshoot the circular equilibrium shape significantly. Consequently the bubble comes to rest still attached to the wall.

A more extensive study of the relation between bubble size and detachment was carried out by simply photographing bubbles of different sizes as they came to rest away from the wall. From each photograph, the diameter of the bubble and the thickness of the liquid layer left between the bubble and the wall were measured. The results obtained are shown graphically in figure 4, where it can be seen that each of the curves exhibits a maximum.

This maximum is best explained by considering the extreme cases: very large and very small bubbles cannot be removed far from the wall. As already mentioned, for large bubbles the surface-tension stresses are (relatively) too weak to cause any significant overshoot of the circular equilibrium position and any subsequent departure. Now, for very small bubbles there can be a sufficient overshoot and curvature variation to produce a pressure gradient which in turn can cause liquid at the base of the bubble to form a liquid gap between the wall and the bubble. But as the bubble is small, a small liquid gap will be sufficient for the interface to regain its circular shape and consequently stop any more liquid flowing towards the wall. Thus the bubble comes to rest very near to the wall.

With this experimental set-up, data cannot be obtained for bubble diameters less than about 5 mm, in which case there can be considerable departures from two-dimensional flow.

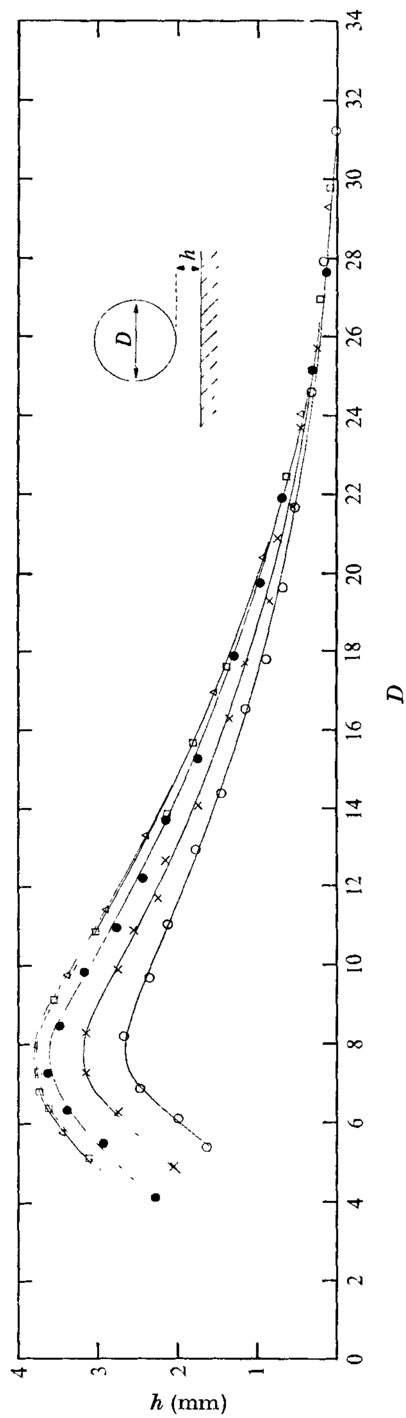

FIGURE 4. Final displacement h of bubble from the wall as a function of bubble diameter D. Air pressure in cm H_2O (gauge): △, 23; □, 19; ●, 15; ×, 11; ○, 7.

3.3. *The effect of bubble growth rate on departure*

Each of the five curves in figure 4 refers to a particular pressure of the air injected into the bubble and therefore to a particular bubble growth rate. Generally, the lower the air pressure the less the displacement from the wall for an air bubble of any chosen size. As foreshadowed in §3.1 above, this can be explained in terms of the bubble shape at the end of growth.

It has already been established (Johnson, de la Pena & Mesler 1966) that bubbles growing fast on a wall tended to be hemispherical. Slowly growing bubbles tend to be spherical and for intermediate growth rates the bubbles are oblate. For oblate bubbles the rounding-off is already under way during growth, the subsequent motion is weaker and the final displacement is less.

For faster growing bubbles the shape is more nearly semicircular and greater displacement is to be expected. There is, however, a limit beyond which an increase in the growth rate of the bubble will not necessarily result in a greater departure from the wall. This is clearly shown on figure 4, where the two top curves, which are for different growth rates, nearly coincide. In both cases the bubbles grew as nearly perfect semicircles with the maximum possible surface-tension potential energy (figures 2 and 3). Any faster growing bubbles would also be nearly semicircular at the end of their growth and consequently would move the same distance away from the wall.

4. Discussion

In this two-dimensional simulation the effect of gravity has been eliminated at the expense of introducing an unknown (and possibly large) resistance to the motion of the bubble, namely that caused by the Perspex plates. Thus the measurements of the final displacement from the wall have little or no quantitative significance. The aim of the experiment, however, has been to show that bubbles do indeed move away from the wall, and also to investigate qualitatively the process of departure. It is believed that, despite the presence of this shear force, the mechanism of departure found herein for the two-dimensional case will be of value in understanding the behaviour of a three-dimensional bubble.

Specifically, the observations of bubbles which grow fast then suddenly stop growing may help in understanding bubbles growing on a heated wall in subcooled boiling. In that situation a bubble may grow fast owing to evaporation from the microlayer and also from the surrounding liquid in the thermal boundary layer; then, when the bubble protrudes into the subcooled liquid there may be condensation on that part of the bubble surface, causing a rapid decrease in the growth rate.

In saturate boiling there is a much slower decay of the growth rate of a bubble and the observations described in this paper are not so readily applicable.

The injection mechanism described above has also been used to inject gas at the underside of a single plate in an attempt to demonstrate departure against gravity in a system with three-dimensional axisymmetric bubbles. This set-up was soon abandoned because it was found that the momentum of the injected air was so high that the bubbles formed were highly elongated in a direction normal to the wall, and also had a peculiar 'wavy' interface. Now in the case of the two-dimensional bubbles, the fact that the gas is injected at right angles to the plates (and not in a direction along the plane of interface propagation) may account for the dispersion of its momentum and for its leaving the interface unaffected.

5. Conclusions

(i) An isothermal experiment with two-dimensional air bubbles formed between parallel plates has been shown to be a useful approximate method for studying, conveniently and on a large scale, the mechanism of bubble detachment from a wall at zero gravity.

(ii) Bubbles growing on a wall have been shown to tend to detach themselves from the wall in the absence of gravity, and even in cases where gravity tends to oppose detachment as shown on figure 5 (plate 2). The separation from the wall is attributed to the surface tension of the gas–liquid interface and the inertia of the liquid. When a bubble stops growing it tends to round off, giving momentum to the surrounding liquid, which makes the interface overshoot the circular equilibrium position. The overshoot surface has higher curvature near the wall, resulting in a pressure gradient which drives liquid towards the base of the bubble and separates it from the wall.

At zero gravity, the distance by which a bubble, in a particular liquid, can be ejected from the wall is found to depend upon the growth rate and the final bubble volume. For a particular growth rate there is a bubble volume for which this distance is maximum. The bubble displacement increases with increasing growth rate but there is a limit beyond which an increase in the growth rate does not give a larger displacement from the wall.

(iii) The experimental results support a previous argument (Madhavan & Mesler 1970) that "on a non-growing initially deformed bubble the gas–liquid surface tension can be a dominant factor causing detachment". On the other hand, the mechanism described differs from those suggesting that the liquid inertia generated by the rapid initial growth is responsible for the ejection of the bubble (Isshiki & Tamaki 1963; Kotake 1969) or that buoyancy is the sole motive force for detachment (Keshock & Siegel 1964; Rehm 1965).

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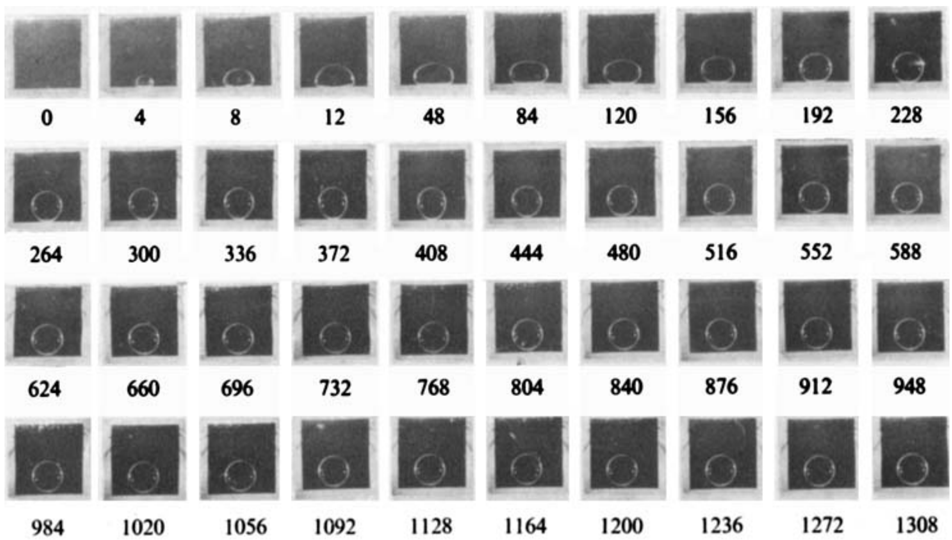

FIGURE 2. Photographs from a film showing a bubble detaching from a wall. The plates are horizontal, the pressure of the air supplied to the bubble is 19 cm H_2O (gauge), air is injected for 12 ms, the time is marked in ms, each side of the black square (painted on the lower Perspex) is 30 mm and the wall is positioned along the lower side of the black square.

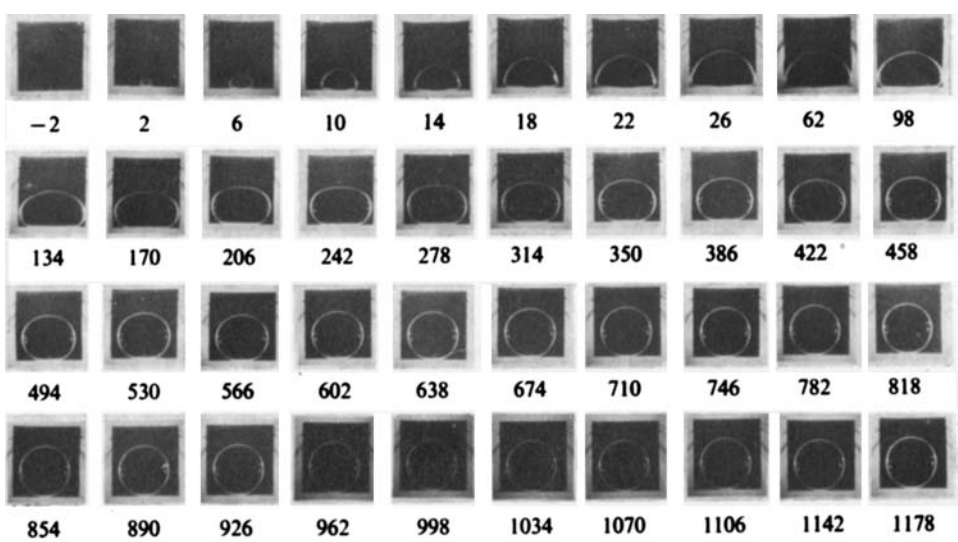

FIGURE 3. Photographs from a film showing a bubble remaining attached to the wall. Air injected for 32 ms; other conditions as in figure 2.

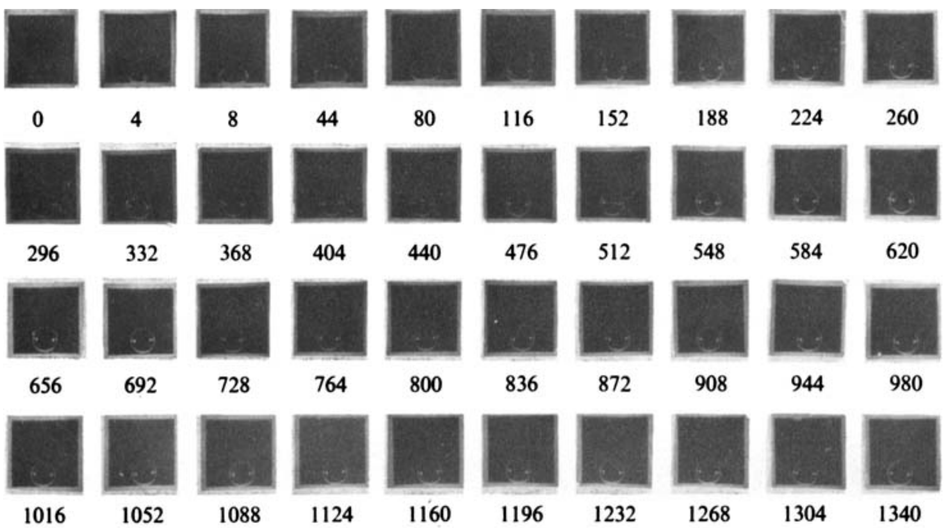

FIGURE 5. Photographs from a film showing a bubble detaching from a wall and then coming back to it owing to gravity. The plates are inclined 10′ to the horizontal and air is injected for 8·5 ms; other conditions as in figure 2.